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MECHANICAL PROPERTY AND MICROSTRUCTURAL EVALUATION OF MARAGING STEELS

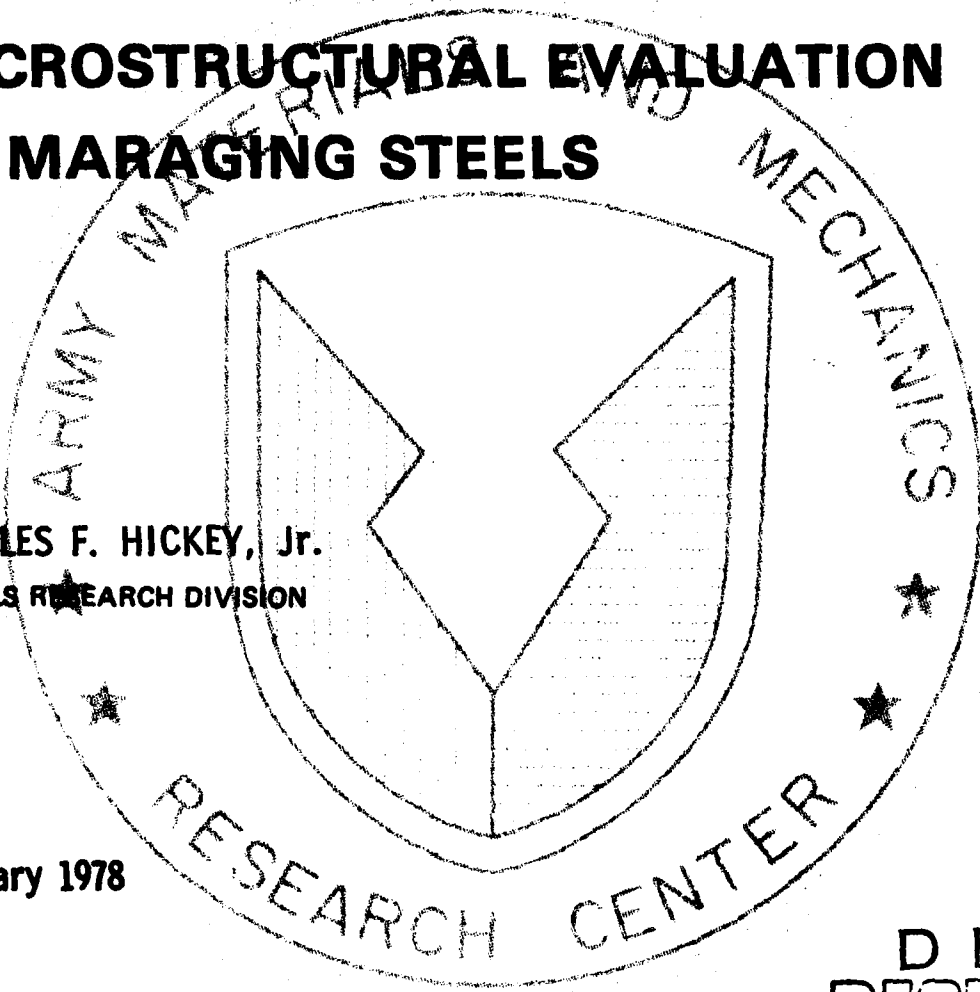
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CHARLES F. HICKEY, Jr.
METALS RESEARCH DIVISION

January 1978

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ABSTRACT

This report contains the results of a material characterization study which was conducted on various grades of 18 percent nickel maraging steel which have been considered for use as the sheath material for the kinetic energy M-735 penetrator. Investigated grades include the 200, 250, 300, and 350. Data presented and discussed are hardness, tensile properties, hoop strength, Charpy impact, and fracture toughness (K_{Ic} , W/A , and K_{Ic}). Additional areas addressed include material processing, chemistry, cleanliness, and heat treatment. Results of the study indicate that the materials generally meet the requirements put forth in MIL-S-46850A, the military specification under which they were procured. The 350 grade is not included in this specification.

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INTRODUCTION

The Army Materials and Mechanics Research Center has recently completed a materials characterization of various grades and heats of maraging steels relative to use as the sheath material for the kinetic energy M-735 penetrator. Portions of this work, including the ballistic performance data, have been published in a confidential report.¹

The purpose of this technical paper is to present all the mechanical property data which have been generated on the investigated grades and heats of maraging steels. Material history such as chemical composition, melting procedure, and heat number will also be included.

MATERIALS

Materials characterized in this investigation were one heat each from the 18 percent nickel (18Ni) 200, 300, and 350 grades of maraging steel and three heats of the 250 grade. Information relative to material history is shown in Table 1. As indicated, the materials were produced by either a vacuum induction melted/vacuum arc remelt (VIM/VAR) or double consumable vacuum remelt (DCVR) process. Chemical compositions (where possible, both producer and AMMRC analysis), are shown in Table 2. The materials were procured under MIL-S-46850A,² which states the chemical composition requirements as shown in Table 3. (The 350 grade is not included in this specification.) In comparing the results of Tables 2 and 3, it can be seen that the composition requirements in some cases have not been met. For example, in the 200 grade, based both on producer and AMMRC analyses, the Mo is slightly higher and the Co slightly lower than specification requirements. Also the Ti content for the 250 grade heat 3592-A and the 300 grade based on the AMMRC analysis is above the maximum stated in the specification. Although a specification does not exist for the 350 grade, the AMMRC analysis for Ti is significantly higher than that reported by the producer.

Typical microstructures for each grade (heat 3592-A for the 250 grade) in the unetched and etched conditions are shown in Figures 1 and 2. J-K inclusions ratings were conducted on all grades and heats of materials and all were found to meet the cleanliness requirements cited in MIL-S-46850A.

TEST PROCEDURE

Longitudinal 0.252-inch-diameter tension and standard 0.394-inch cross-section Charpy V-notch impact specimens (LR orientation) were machined from 1-1/2-inch-diameter bar. Fracture toughness data (K_{IC} , W/A , and K_{ID}) were generated from Charpy specimens which were fatigue cracked approximately 0.050 inch and then broken in slow bend. It is important to note that all data except those obtained from the Carpenter 250 grades are from material heat treated in 1-1/2-inch-diameter bar form.

1. ANCTIL, A. A., et al. *Metallographic and Mechanical Property Characterizations of DT-II Tungsten Cases, Steel Sheath, and DT-II Steel Armors for the M-735 Projectile Program (U)*. Army Materials and Mechanics Research Center, AMMRC SP 77-2, March 1977 (Confidential Report).
2. *Steel Bar, Plate, Sheet, Strip, Forgings, and Extrusions, 18 Percent Nickel Alloys, Maraging, 200 KSI, 250 KSI, and 300 KSI, High Quality*. Military Specification, MIL-S-46850A, 18 September 1969.

Table 1. MATERIAL HISTORY

| Grade | 200 | 250 | | 300 | 350 |
|----------|----------------|----------------|-------------|----------------|--------|
| Producer | Special Alloys | Teledyne Vasco | Carpenter | Teledyne Vasco | |
| Process | VIM/VAR | DCVR | VIM/VAR | DCVR | |
| Heat | 6711-J | 3592-A | 92535 92537 | 4092-A | 4177-A |

Table 2. CHEMICAL ANALYSES (WEIGHT PERCENT)

| Grade | 200 | | 250 | | | | 300 | | 350 | |
|---------|---------|-------|--------|-------|---------|---------|--------|-------|--------|-------|
| Process | VIM/VAR | | DCVR | | VIM/VAR | VIM/VAR | DCVR | | DCVR | |
| Heat | 6711-A | | 3592-A | | 92535 | 92537 | 4092-A | | 4177-A | |
| Element | (1) | (2) | (1) | (2) | (1) | (2) | (1) | (2) | (1) | (2) |
| C | 0.018 | 0.018 | 0.020 | 0.018 | 0.006 | 0.003 | 0.020 | 0.027 | 0.011 | 0.016 |
| Si | 0.01 | 0.01 | 0.04 | ND | 0.01 | 0.05 | 0.06 | <0.07 | 0.05 | <0.07 |
| Mn | 0.10 | 0.08 | 0.05 | 0.04 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 |
| S | 0.002 | 0.001 | 0.003 | 0.001 | 0.005 | 0.006 | 0.005 | 0.004 | 0.004 | 0.004 |
| P | 0.008 | 0.011 | 0.006 | 0.009 | 0.003 | 0.005 | 0.004 | 0.009 | 0.005 | 0.008 |
| Cr | ND | ND | 0.07 | 0.17 | 0.09 | 0.07 | 0.15 | 0.24 | 0.10 | 0.11 |
| Mo | 4.10 | 4.44 | 4.83 | 4.59 | 4.71 | 4.99 | 4.94 | 4.63 | 4.74 | 4.64 |
| Co | 7.45 | 7.66 | 7.88 | 8.35 | 7.21 | 6.99 | 9.36 | 9.69 | 11.7 | 12.5 |
| Ni | 17.2 | 17.7 | 18.2 | 17.9 | 18.6 | 18.8 | 18.3 | 18.2 | 18.3 | 17.9 |
| Al | 0.09 | 0.07 | 0.14 | 0.14 | 0.09 | 0.14 | 0.12 | 0.13 | 0.14 | 0.11 |
| Ti | 0.23 | 0.24 | 0.43 | 0.51 | 0.42 | 0.35 | 0.59 | 0.92 | 1.36 | 1.52 |
| N | - | 0.004 | - | 0.005 | - | 0.003 | - | 0.007 | - | 0.007 |
| O | - | 10.0 | - | 10.0 | - | 15.0 | - | 11.0 | - | 15.0 |
| H | - | 0.2 | - | 0.1 | - | 0.1 | - | 0.1 | - | 0.1 |

(1) Producer Analysis

(2) AMMRC Analysis

(3) PPM

Table 3. CHEMICAL COMPOSITION REQUIREMENTS (WEIGHT PERCENT)

| Element | Grade 200 | Grade 250 | Grades 300 and 300A | Check Analysis Permissible Variation |
|--|--------------|--------------|---------------------|--------------------------------------|
| Nickel | 17.0 - 19.0 | 17.0 - 19.0 | 18.0 - 19.0 | ±0.15 |
| Cobalt | 8.0 - 9.0 | 7.0 - 8.5 | 8.5 - 9.5 | ±0.10 |
| Molybdenum | 3.0 - 3.5 | 4.6 - 5.2 | 4.6 - 5.2 | ±0.10 |
| Titanium | 0.15 - 0.25 | 0.3 - 0.5 | 0.5 - 0.8 | ±0.05 |
| Aluminum | 0.05 - 0.15 | 0.05 - 0.15 | 0.05 - 0.15 | ±0.03 |
| Carbon | 0.03 Maximum | 0.03 Maximum | 0.03 Maximum | +0.005 |
| Manganese | 0.10 Maximum | 0.10 Maximum | 0.10 Maximum | +0.03 |
| Silicon | 0.10 Maximum | 0.10 Maximum | 0.10 Maximum | +0.02 |
| Phosphorous | 0.01 Maximum | 0.01 Maximum | 0.01 Maximum | +0.002 |
| Sulfur | 0.01 Maximum | 0.01 Maximum | 0.01 Maximum | +0.002 |
| Residual Elements | - | - | - | |
| Iron | Balance | Balance | Balance | |
| Selectable Allowable Maximum Additions | | | | |
| Boron | 0.003 | 0.003 | 0.003 | Certified as Additions Only |
| Zirconium | 0.020 | 0.020 | 0.020 | |
| Calcium | 0.050 | 0.050 | 0.050 | |

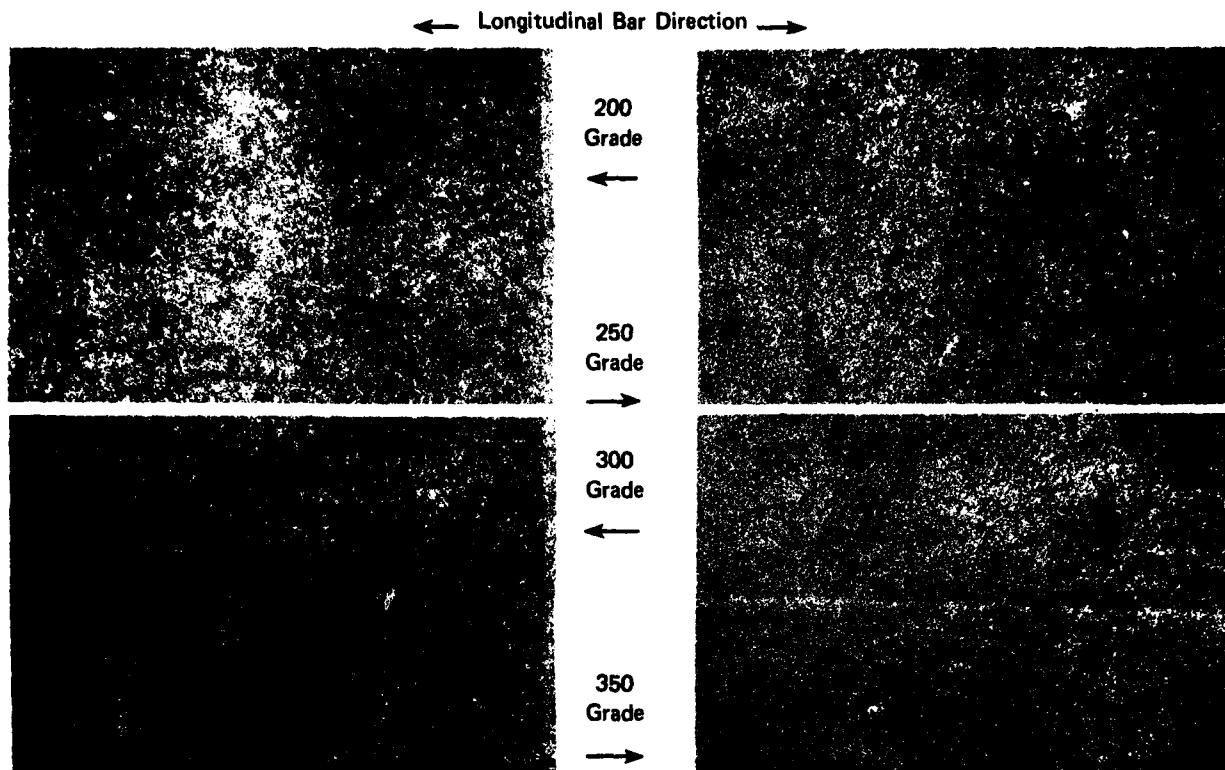


Figure 1. Microstructure of aged maraging steels in unetched condition. Mag. 100X

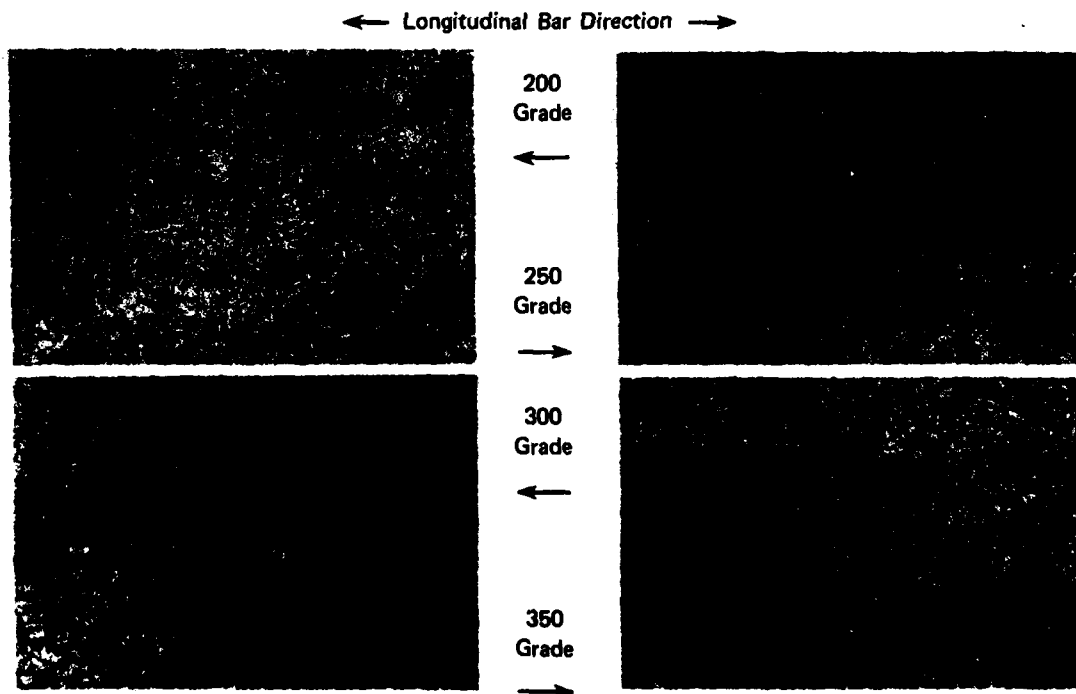


Figure 2. Microstructure of aged maraging steels. Mag. 250X (Maraging Etch: 5g FeCl_3 , 2 ml HCL, 296 ml $\text{C}_2\text{H}_5\text{OH}$)

Data for heat 92535 are from specimens machined from solution-treated 1-1/2-inch-diameter bar and aged in the finished machined condition; heat 92537 specimens were blanked from solution-treated 1-1/2-inch-diameter bar, aged, and finish machined. Heat treatments are defined in Table 4.

RESULTS AND DISCUSSION

Hardness and Tensile Properties

Hardness and tensile properties obtained in this investigation are shown in Table 5 and minimum requirements as set forth in MIL-S-46850A in Table 6. Hardness and elongation requirements are met in all cases, but yield strength is somewhat low for the 250 grade heat 3592-A and the 300 grade. Respective values are 233 and 269.9 ksi and minimum requirements are 240 and 280 ksi. Differences in solution temperatures and aging times should be considered relative to the strength variation within the heats of the 250 grade material. As shown in the Aerospace Structural Metals Handbook,³ an increase in solution temperature from 1550 to 1650 F can decrease the strength slightly; however, an increase in aging time from 3 to 5 hours for the 1650 F solution temperature can result in a yield and tensile strength increase of 10 ksi (Handbook Figure 3.021422).

Hoop strength as determined by a pressurized ring test on a Stanford Research Institute 10,000-psi capacity expanded ring tester is listed in Table 7. Data for the 200 and 250 (heat 3592-A) grades were obtained at strain rates of 0.02 inch/inch/second and 0.7 inch/inch/second. The tangential tensile strength values tend to increase as a function of strain rate. Tangential strength for the 200 grade at the slower strain rate approximates the unidirectional ultimate tensile strength results - 212 versus 208 ksi. For the 250 grade, the hoop strength at the higher strain rate approximates the unidirectional data - 239 versus 235 ksi.

Realizing that there are differences such as specimen finish, volume, and stress distribution which can exist between a unidirectional and a ring-type tension test, it can be concluded that in this investigation the data indicate reasonably good agreement between the two types of tests.

Toughness

Toughness parameter data are presented in Table 8 for tests conducted at room temperature. Charpy impact values ranged from 60.0 ft-lb for the 200 grade to 8.0 ft-lb for the highest strength 350 grade. As would be expected due to the yield strength variation within the 250 grade heats, a toughness difference is also evidenced. Heat 3592-A exhibited the highest toughness of 30.0 ft-lb within the 250 grade, whereas for the other two heats the values were 24.9 ft-lb.

Fracture toughness data (K_Q and W/A) followed the same overall trend as that shown by the impact data. K_Q values ranged from 131.2 ksi $\sqrt{\text{in.}}$ for the 200 grade to 25.1 ksi $\sqrt{\text{in.}}$ for the 250 grade. Respective W/A values were 3281.0 and 65.2 in.-lb/in.². Within the 250 grade, heat 3592-A again had the highest values.

3. 18Ni (250) Maraging. Aerospace Structural Metals Handbook, Chapter Code 1220, Mechanical Properties Data Center, Traverse City, Michigan.

Table 4. HEAT TREATMENT

| Grade | Heat | Heat Treatment |
|-------|--------|---------------------------------------|
| 200 | 6711-J | 1500 F - 1 Hr - AC; 900 F - 3 Hr - AC |
| 250 | 3592-A | 1500 F - 1 Hr - AC; 900 F - 3 Hr - AC |
| | 92535 | 1650 F - 1 Hr - AC; 900 F - 5 Hr - AC |
| | 92537 | 1650 F - 1 Hr - AC; 900 F - 5 Hr - AC |
| 300 | 4092-A | 1500 F - 1 Hr - AC; 900 F - 3 Hr - AC |
| 350 | 4177-A | 1500 F - 1 Hr - AC; 950 F - 3 Hr - AC |

Table 5. HARDNESS AND TENSILE PROPERTIES

| Grade | 200 | 250 | | | 300 | 350 |
|------------------------|--------|--------|-------|-------|--------|--------|
| Heat | 6711-J | 3592-A | 92535 | 92537 | 4092-A | 4177-A |
| Hardness HRC | 44.2 | 48.7 | 49.0 | 50.3 | 53.5 | 59.1 |
| Tensile Properties | (1) | (1) | (2) | (3) | (1) | (1) |
| Y.S., 0.2% Offset, ksi | 202.5 | 232.0 | 240.5 | 240.0 | 270.0 | 321.0 |
| | 203.5 | 234.0 | 242.5 | 239.2 | 269.8 | 325.0 |
| | 203.0 | 233.0 | 241.5 | 239.6 | 269.9 | 323.0 |
| U.T.S., ksi | 207.5 | 234.0 | 247.5 | 246.0 | 273.0 | 329.0 |
| | 207.5 | 236.0 | 245.5 | 245.2 | 273.8 | 330.0 |
| | 207.5 | 235.0 | 246.5 | 245.6 | 273.4 | 329.5 |
| Elongation, % | 13.3 | 14.0 | 11.5 | 12.5 | 11.0 | 10.0 |
| | 11.1 | 14.0 | 11.5 | 13.5 | 11.0 | 10.0 |
| | 12.2 | 14.0 | 11.5 | 13.0 | 11.0 | 10.0 |
| R.A., % | 64.8 | 58.4 | 60.0 | 55.8 | 48.0 | 34.8 |
| | 63.7 | 59.4 | 59.0 | 58.4 | 50.1 | 36.0 |
| | 64.3 | 58.9 | 59.5 | 57.1 | 49.1 | 35.4 |

(1) Specimens machined from heat-treated 1-1/2-inch-diameter bar.

(2) Specimens machined from solution-treated 1-1/2-inch-diameter bar and aged in finish machined condition. Data supplied by Carpenter Technology Corporation.

(3) Specimens blanked from solution-treated 1-1/2-inch-diameter bar, aged, and finished machined.

Hardness data are average of 5 readings.

Table 7. HOOP STRENGTH AS DETERMINED BY EXPANDED RING TESTER

| Grade | Strain Rate | Spec. | Tensile Strength ksi |
|--------------------|---------------------------|-------|----------------------|
| 200 Heat 6711-J | 0.02 inch/ inch/second | 2 | 212 |
| | 0.7 inch/ inch/second | 4 | 223 |
| 250 Heat 3592-A | 0.02 inch/ inch/second | 1 | 239 |
| | | 2 | 209 |
| | | 3 | 212 |
| | 0.7 inch/ inch/second | | 220 (Avg.) |
| | | 4 | 211 |
| | | 5 | 238 |
| | | 6 | 267 |
| | | | 239 (Avg.) |

Table 6. LONGITUDINAL MECHANICAL PROPERTIES OF BAR, PLATE, FORGINGS, AND EXTRUSIONS
(Minimum Requirements Specified by MIL-S-46850A)

| Grade | Hardness HRC | Tensile Properties | |
|-------|--------------|----------------------------|-----------------|
| | | Y.S. 0.2% Offset ksi | Elongation % |
| 200 | 44 | 200 | 8.0 |
| 250 | 48 | 240 | 6.0 |
| 300 | 52 | 280 | 5.0 |

Table 8. TOUGHNESS PROPERTIES

| Grade | 200 | 250 | | 300 | 350 | |
|------------------------------------|--------|--------|-------|-------|--------|--------|
| Heat | 6711-J | 3592-A | 92535 | 92537 | 4092-A | 4177-A |
| Toughness Properties | (1) | (1) | (2) | (3) | (1) | (1) |
| C_V , ft-lb | 60.9 | 30.2 | 26.8 | 24.7 | 17.5 | 8.6 |
| | 59.1 | 29.8 | 25.1 | 24.7 | 18.1 | 7.3 |
| | 60.0 | 30.0 | 22.9 | 25.4 | 17.8 | 8.0 |
| | | | 24.9 | 24.9 | | |
| K_Q , ksi $\sqrt{\text{in.}}$ | 130.9 | 104.4 | 99.2 | 100.7 | 73.9 | 35.2 |
| | 128.4 | 112.5 | 96.5 | 100.4 | 65.5 | 35.2 |
| | 134.2 | 113.5 | 98.2 | 105.2 | 70.9 | 34.8 |
| | 131.2 | 110.1 | 98.0 | 103.4 | 70.1 | 35.1 |
| W/A, in.-lb/in. ² | 2790.8 | 1256.4 | 876.4 | 777.3 | 355.0 | 70.8 |
| | 3228.2 | 1612.7 | 830.9 | 849.8 | 368.7 | 61.9 |
| | 3824.0 | 1505.3 | 839.2 | 902.1 | 397.1 | 62.9 |
| | 3281.0 | 1458.1 | 848.8 | 842.3 | 373.6 | 65.2 |
| K_{Id} , ksi $\sqrt{\text{in.}}$ | | | 84.4 | | | |
| | | | 83.5 | | | |
| | | | 85.0 | | | |
| | | | 84.3 | | | |

(1) Specimens machined from heat-treated 1-1/2-inch-diameter bar.

(2) Specimens machined from solution-treated 1-1/2-inch-diameter bar and aged in finish machined condition. Data supplied by Carpenter Technology Corporation.

(3) Specimens blanked from solution-treated 1-1/2-inch-diameter bar, aged, and finished machined.

Dynamic fracture toughness data (K_{Id}) were generated from the 250 grade heat 92535. The K_{Id} average value of 84.3 ksi $\sqrt{\text{in.}}$ which was obtained should be considered for information purposes only, since standards have yet to be adopted for this test. The corresponding K_Q value was 98.0 ksi $\sqrt{\text{in.}}$

It is interesting to note that MIL-S-46850A does not contain a Charpy V-notch or fracture toughness (K_{Ic}) requirement. However, the updated version (MIL-S-46850B, dated 24 June 1976) does stipulate a minimum K_{Ic} of 50 ksi $\sqrt{\text{in.}}$ for the 300 grade. K_Q data can only be considered as conditional K_{Ic} ; however, based on the average value of 70 ksi $\sqrt{\text{in.}}$ which was obtained in this investigation, it would appear that the 300 grade would meet the toughness requirements of the updated specification.

SUMMARY AND RECOMMENDATION

1. Based upon the results of this study, it appears that all investigated grades and heats of maraging steel constitute good heats of material. Although the strength was slightly low for the 250 grade heat 3592-A and for the 300 grade, this is most likely explained through heat treatment history.

2. It is recommended that MIL-S-46850B be expanded to include the 350 grade. Also, since the maraging steels are being used or considered for numerous applications where toughness is an important design parameter, it is further recommended that MIL-S-46850B be modified to include an impact (C_V) and K_{Ic} minimum requirement for the various grades. If sufficient toughness parameter data are not available to establish such minimum requirements, then a data package should be generated.

ACKNOWLEDGMENTS

The author wishes to thank Messrs. S. Doherty, K. Rollins, and P. Lum for their technical assistance; also, Teledyne Vasco, Chamberlain Manufacturing Corporation, and Carpenter Technology Corporation for supplying the materials.

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